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TITLE THE DESIGN AND INSTALLATION OF A CORE DISCHARGE MONITOR FOR CANDU-TYPE REACTORS

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THE DESIGN AND INSTALLATION OF A CORE DISCHARGE MONITOR
FOR CANDU-TYPE REACTORS

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ABSTRACT

A new type of surveillance system that monitors neutron and gamma radiation in a reactor containment is being installed at the Ontario Hydro Darlington Nuclear Generating Station A, Unit 2. Unlike video or film surveillance that monitors mechanical motion, this system measures fuel-specific radiation emanating from irradiated fuel as it is pushed from the core of CANDU-type reactors. Proof-of-principle measurements have been carried out at Bruce Nuclear Generating Station A, Unit 2. The system uses (γ,n) threshold detectors and onization detectors. A microprocessor-based electronics package, GRAND-II (Gamma Ray And Neutron Detector electronics package), provides detector bias, preamplifier power, and signal processing. Firmware in the GRAND-II controls the surveillance activities, including data acquisition and a level of detector authentication, and it handles authenticated communication with a central data logging computer. Data from the GRAND-II are transferred to an MS-DOS-compatible computer and stored. These data are collected and reviewed for fuel-specific radiation signatures from the primary letector and proper ratios of signals from secondary detectors.

INTRODUCTION

To fulfill the International Atomic Energy Agency (IAEA) safeguards criteria for CANDU reactors, an approach for safeguarding core fuel was needed.[1] The size and structure of the reactor containments at large multiple-unit stations are not well suited for safeguarding by classical surveillance systems. Proposed alternatives, using short-notice random inspections, required operational human resources that were not available to the IAEA.[1] Additionally, such a safeguards approach is very intrusive to the facility.

The results from proof-of-principle (POP) measurements[2] showed that Be(γ,n) or D(γ,n) threshold detectors and nielded and unshielded ionization chambers (ICs) can be used to observe fuel from the time it is discharged from a CANDU reactor until it is transferred to a temporary spent-fuel storage area. It was proposed that a combination of these detectors could be used as a core discharge monitor (CDM) at CANDU reactors. Whereas the initial installation costs for such a system may be significantly higher than for the more classical

alternatives, it was projected that over a few years the savings in operating costs will offset the higher up-front costs. Also, there was no way to obtain the additional manpower for the alternatives.

A decision was made to install such a CDM system at the Ontario Hydro Darlington Nuclear Generating Station A, Unit 2 reactor. Two pairs of (γ,n) threshold detectors and shielded and unshielded ICs operating in the current mode were specified for the CDM. A modified version of the GRAND-I, the GRAND-II, would power the detectors and collect and store their data. The GRAND-II independently carries out the CDM function, but it relies on a central computer to periodically off-load data from its internal storage. This computer also provides a focal point for the various GRAND-IIs that are used throughout the station. A sophisticated CANDU REVIEW program was specified to enable the inspector to conveniently review up to 65 days of inspection data in a very short time.

This system implementation has been spearheaded by a four-person team. They have had the support of IAEA personnel, the facility, private contractors, and national laboratories through state support programs. Work was also contracted to private firms in Austria, Canada, and the United States.

THE DARLINGTON UNIT 2 CDM SYSTEM

The CDM system is designed to collect and save monitoring data from the reactor vault that will allow the IAEA to certify facility compliance to safeguards agreements. The system should be reasonably safe from tampering, and one should be able to authenticate the stored data. The system should be able to operate through reasonable length power outages. It should be very reliable and any maintenance should not require access to the reactor vault.

The results from POP measurements[2] were obtained from detectors and electronics temporarily mounted on a fueling trolley that travels between all reactors and a central storage area. Detectors so mounted were able to monitor fuel from the time it was discharged from the reactor until it was transferred to a spent-fuel storage area. In this facility, permanent installation of IAEA equipment on a fueling machine or trolley was

not allowed. Hence the detectors were mounted on the walls of the reactor very close to the geometrical plane of the end-channel caps. (It is the opinion of the designers that if such an implementation is possible the best system design would make use of detectors on the trolley and a very limited complement of detectors in each reactor vault.)

The request was to design a highly reliable system with a 20-year maintenance-free lifetime. The designers did not want to make such a commitment without previous experience; however, the elements of the system that were to be included in the containment are highly reliable and no active electronic components are inside the vault.

Hardware

The system has three major parts:

- the monitoring subsystem,

- a central focus computer (CFC), and

- a data review system.

The monitoring subsystem, which includes the detectors, the preamplifiers and electronics unit, and the cables and reactor containment penetrations necessary to connect the detectors to the electronics, carries out the CDM functions. The electronics unit, the GRAND-II, provides bias to the detectors and power for the preamplifiers. The resident CDM firmware (software installed in nonvolatile memory) takes and stores

data from the detectors. The features of the firmware are discussed later. The GRAND-II is connected to the electrical mains, but it has built-in battery capacity for greater than 24-hour stand-alone operation. It has a significant amount of battery backed up random-access memory for data storage.

A block diagram of the CDM data collection system without the review computer is shown in Fig. 1, a schematic top view of the reactor vault. The core fuel channels are accessed on the left and right faces of the reactor. Two CDM detector enclosures are mounted on the lower wall as shown in the figure. Cables from the left detector enclosure go out of the containment through the electrical penetration labeled EP. The two ionization chamber signal cables go directly to a GRAND-II located in a metal box, DACM, which is under IAEA seal. One of the two threshold detector cables goes to a preamplifier with an analog output. The cable from this output goes to the GRAND-II in the left, or adjacent, DACM box. The other threshold detector cable goes to a preamplifier with a digital output, which goes back through the penetration, along the inside wall to a splice box, and then onto and through the penetration adjacent to the right, or remote, GRAND-II, and finally to the GRAND-II in the remote DACM. The description of the right detector enclosure and its signal lines is analogous. To provide a level of redundancy, each GRAND-II receives threshold detector signals from both reactor faces. Preamplifiers are powered by the GRAND-II that receives its signals.

The figure also shows a link from the GRAND-IIs to the CFCs. The original concept was to have a computer that
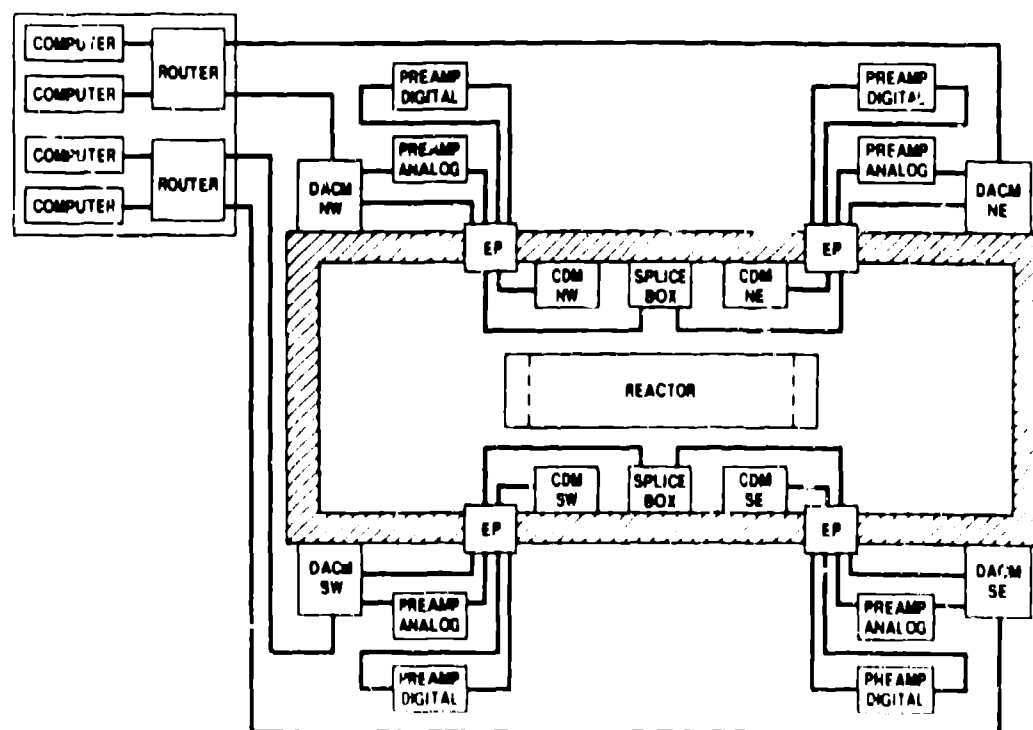

Fig. 1. Unit 2 CDM data collection system.

would connect to the GRAND-IIs at the left faces of all the reactors. A second computer would connect to all GRAND-IIs at the opposite faces. Each would have a backup computer that would take over if a fault developed in the primary computer. In the Darlington Unit 2 installation, it was simpler to provide a computer for each GRAND-II. For this case, the redundancy and number of computers is equivalent to the proposed case, but the inspector must focus on four computers instead of two. The serial links are isolated current loops that can reliably transfer data at 19.2-k baud. The link may be up to 360 m long at Darlington. It has been tested to 210 m.

The original, and still recommended, configuration for the monitor subsystem is shown in Fig. 2. The figure shows the preamplifiers mounted inside the electronics enclosure. Because the length of cable between the detectors and the preamplifiers was limited to less then 3 m, and conflicted with where the electronics enclosures could be mounted, the preamplifiers installed in unit 2 were not placed inside the enclosure. This is not recommended in general. A sealed enclosure should be installed to prevent access to the preamplifiers and cable connections.

The detectors are contained in metal boxes that bolt to the walls. The primary detectors (the ones thought to be hardest to fool) are the $D(\gamma,n)$ detectors. There are two detectors of this type. Each is made from a pair of fission chambers, each of which is placed inside a high-density, polyethylene-lined, dry well that extends into a rectangular container of D_2O. The container has two isolated compartments, each with two separate compartments. Th $_2O$ volume of the container is approximately 40 L. The container is surrounded by 5 cm of high-density polyethylene that has an 8-mm cadmium sheet on its outside surface.

There are also two secondary detectors. Each is built from a 57-cm-long by 1.6-cm-diam IC mounted in a closed 2.125-cm-diam stainless-steel cylinder with 1.625-cm-thick walls. The ion chambers are filled with xenon gas at 10 atm. One of these cylinders is also mounted inside a 2.5-cm-thick cylindrical lead shield. The latter is called the shielded IC, the other the bare IC. The ICs share a single bias source and sit on top of the polyethylene, which rests on the D_2O container. A small,highly reliable double pole relay inside the metal enclosure disconnects the ICs from the signal cable to allow the leakage of the cables to the GRAND-II to be measured. The state of the relay is controlled by the GRAND-II, and in the absence of power, the contacts are closed; hence, if failure does occur it should not affect the normal operation of the detectors.

Signal penetrations into the detector enclosure are provided by six radiation-hard type "N" bulkhead connectors. All neutron signal and bias cables inside the detector enclosure are special radiation-hard RG-71 characteristic double-shielded cables. The detector enclosure mounts to the wall of the containment with four bolts. If replacement is necessary (an *extremely unlikely* possibility) six type N connectors must be unscrewed and four bolts and a facility ground strap removed to allow the detector enclosure to be transported. A spare unit installs just as easily.
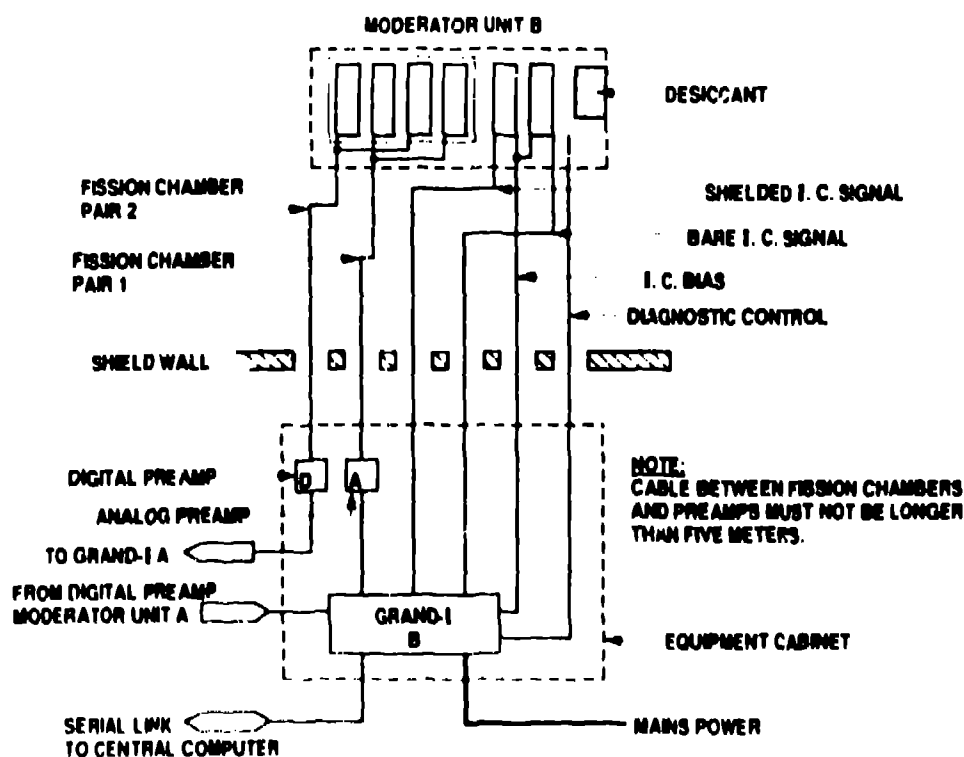

Fig. 2 Schematic representation of monitor subsystem.

Because this was the first installation of its kind, it was decided by the IAEA to provide additional redundancy by instrumenting the opposite wall of the reactor vault. If the system proves reliable, the equipment on the far side may be used for other reactors.

The basic firmware in the GRAND-II provides drivers for the personality boards (see Appendix) used with the detectors and supports a powerful external communications and control package. It also supports USER programs that can be written for specific applications and which make use of the drivers in the basic firmware. A special USER function for the CDM was specified, which includes the following features:

- Collect, filter, and store data from the detectors;

- Identify the conditions indicating irradiated fuel outside the reactor core;

- Collect and store instrument performance data;

- Transfer data (with retransmission capabilities) on command from CFC;

- Sense possible detector tampering;

- Authenticate detector enclosure by "fingerprint,"

- Work with CFC software to authenticate the GRAND-II—CFC link,

- Provide sleep-with-random-wake-up function to extend operation time during power outages.

The detector authentication by "fingerprint" and the random wake-up features have not yet been totally implemented. Hardware exists, but firmware needs to be written. Its implementation is still considered important. In the meantime, detector authentication can be carried out off-line using a program written for the CFC computers. This program controls the operation of the GRAND-II, receives data, and stores it in a file. The file is then analyzed using a Symphony-based review program. This implementation is not acceptable in the long term because it requires the presence of an inspector to install an electronic key on the GRAND-II. Without this key, the GRAND-II will not respond to any command that will interfere with normal CDM activities. When the key is installed, the electronics enclosure must be resealed or an inspector must remain to prevent access to the communication authentication keys that reside in the GRAND-II. After the fingerprint has been made, the electronics enclosure must be resealed. When fingerprinting is implemented in the firmware, the GRAND-II will automatically make the fingerprint periodically or when a possible tamper is sensed. Inspector presence and seal breaking will not be required.

SOFTWARE

The CFCs are MS-DOS-compatible AT-type personal computers. In the original specification, they interface by serial ports to up to four GRAND-IIs. Initially, they are configured with 40-Mbyte hard-disk drives for data storage and removable Bernoulli drives for data transfer. Higher capacity internal storage is required for multiple reactor service. Depending on how redundancy is provided, techniques such as disk mirroring may be advisable. Uninterruptible power supplies (UPS's) with a capacity to allow the CFCs to off-load all data from the GRAND-IIs are provided for the CFCs. When used in conjunction with higher capacity UPS's and an appropriate "watch dog," the CFCs can be shut down after all data have been transferred from the GRAND-IIs until the GRAND-II's memory is full. The CFCs are then powered up again and the data are off-loaded one more time.

The following CFC software functions are included:

- Communicate with multiple GRAND-IIs to off-load monitor performance data;

- Work with GRAND-II software to authenticate the GRAND-II—CFC link;

- Monitor status indicators from GRAND-IIs, report anomalies in semi-real time, and log them to disk;

- Provide for and manage storing of monitoring and performance data on the hard disk;

- Provide for the transfer of data to removable media; and

- Communicate with a "watch-dog" to automatically restart the CFC if it fails, announce anomalies, and manage the UPS.

We intended to provide for the simple and graphical online viewing of stored monitoring data using the CFC monitor. However, this was not implemented because of lack of resources to write the software. However, we still believe that this is a worthwhile feature.

Data are now reviewed at the end of the inspection period, when an inspector uses the program running in the CFC to copy the stored data to a removable cartridge to be taken to a REVIEW computer where the results of the fueling activities are reconciled with the facility operator's declaration and/or bundle counter information.[3] Bundle counters count the irradiated bundles discharged from the fueling machines. Although the REVIEW program could reside in the CFC, this would complicate procedures and disk storage and would require the interruption of the normal CDM program in the CFC. Inspectors felt they did not want review data in the small and noisy environment of the CFC computer room. Hence it was decided that the REVIEW program should reside

in an off-line computer so data could be reviewed in a separate room at the facility, or at the IAEA regional office or headquarters. The data dump feature of the CFC's CDM program was added to keep the inspector from having to interface with more than one program. This reduces the probability of not having the proper program running when the inspector leaves the facility.

The original specification was for the data to be reviewed using graphs of data from various detectors in the reactor containment room. (Figure 3 shows data from the POP measurements plotted by a prerelease version of the CDM REVIEW software.) Up to four graphs can be displayed simultaneously. Initially, it was thought that data for up to four reactors would be held in the data base; however, because of the very large amount of data, the import time to the data base can be very long if more than a single reactor's data is in the data base. Roughly 10 000 data points can be displayed on a graph at one time. To increase the readability of the data, the display can be expanded about the cursor. Events of interest on the display can be tagged with the associated time using an interactive cursor and a keystroke. In addition or alternatively, the number of events also can be counted and entered per day. Hard copies of the events-of-interest file and the data are obtainable. The user interface is menu driven and conforms to the IAEA specification. A parameter table for default values is provided and is accessible from a menu.

The CANDU REVIEW program builds on and significantly enhances work originally done by Los Alamos for IAEA Safeguards at the Plutonium Fuel Production Facility in Japan.[4] The capabilities and specifics of the CANDU REVIEW program will be the subject of a subsequent paper.*

A utility program was written for the CFC that allows for remote control of the GRAND-IIs from the keyboard and monitor at the CFC. This allows remote diagnostics to be run (the electronic key must be installed). The communications program, CARBON COPY, has been used to communicate between Los Alamos and a Darlington IAEA computer. Hence in the event of a malfunction in a GRAND-II, a specialist can link to the CFC controlling that GRAND-II and attempt to diagnose the problem. Obviously, such communication must be authorized by both the IAEA and facility operators. During normal operation the phone lines are *not* connected to the computers.

IMPLEMENTATION

The original time schedule called for designing and installing the system in less than 1 year. The time pressure dictated some compromises and short cuts. It was felt that the only way to meet that schedule was to have the IAEA do much of the work itself.

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*For information, contact Shirley Klosterbuer, Los Alamos National Laboratory, MS E540, Los Alamos, NM 87545.
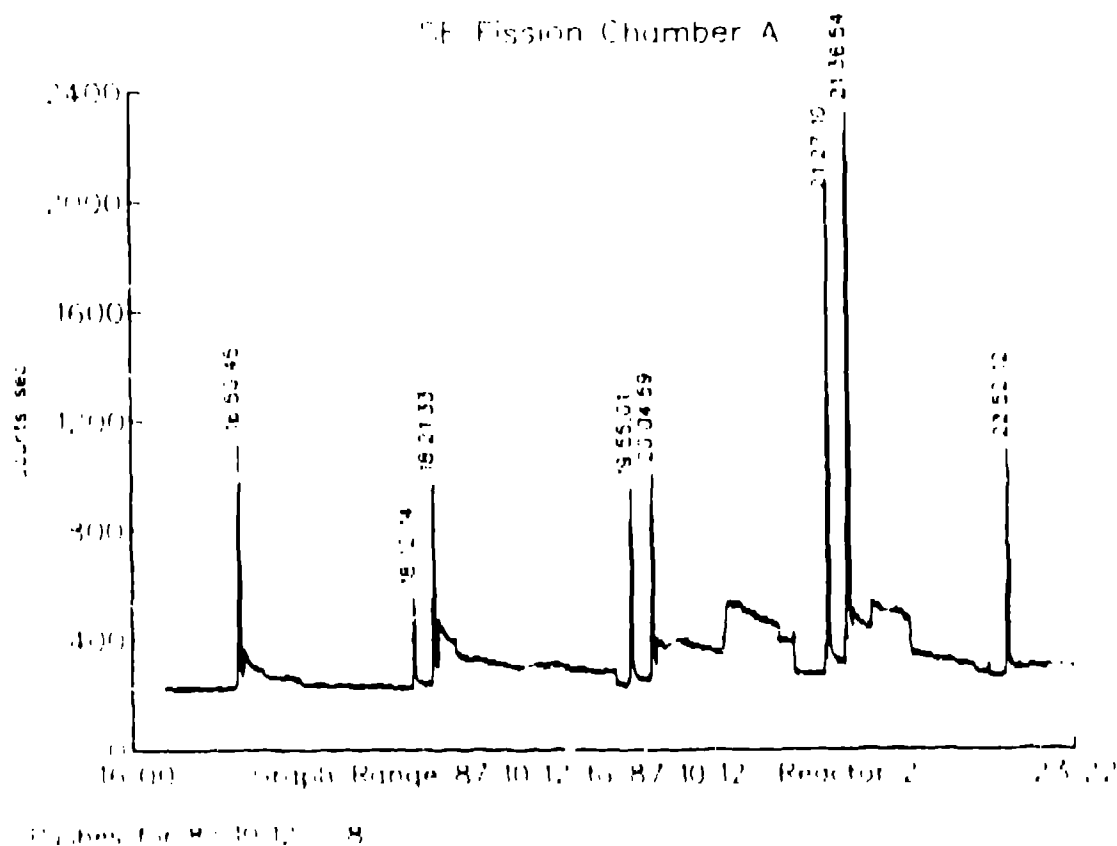

Fig. 3. Data from POP plotted by a prerelease version of CDM REVIEW

... details of the implementation of this system could fill a paper; only an outline will be given here. The implementation team from the IAEA consisted mainly of four people: a liaison between the IAEA, the facility, and the Canadian safeguards support program (CSSP); a coordinator, expeditor, and systems engineer; a physicist/designer, and an electrical technician. These people enjoyed the support of the IAEA Safeguards Section for Instrument and Field Support, the Section for Instrument and Equipment Provision and Management (SGDID), consultants to the Canadian Atomic Energy Control Board (SGDIM), physics and software consultants, firmware and software developers and electrical and mechanical fabricators from the Los Alamos National Laboratory (through the United States support program), and private design and fabrication firms. The mix of expertise was good; however, more people should have been assigned.

We developed a conceptual design for the overall system and wrote a first draft of a functional specification. (The functional specification was continually revised during early development.) We specified and ordered ionization and fission chambers. The mechanical design of the detectors and assemblies was developed in Vienna. Digital and analog preamplifiers were designed (specifically for this application) and built in Vienna. From the experience of the POP, modifications to the GRAND-I hardware and firmware were specified. Some hardware modifications were included in the GRAND-II by the manufacturer, others were implemented by the IAEA staff. Los Alamos modified the GRAND-I firmware and implemented the IAEA's specifications in the special CDM USER function. Special splice boxes were designed and built by the IAEA to join cables without using connectors. These boxes should be more reliable than connectors and saved the cost of radiation-hard connectors, which also had a very long delivery time. The detector and GRAND enclosures and parts were built by a private firm. Detectors, except for the ICs and D₂O, were placed inside the enclosures and checked at Los Alamos by IAEA and Los Alamos personnel. The preamplifiers were tested and adjusted by Los Alamos before the arrival of the IAEA. Los Alamos technicians helped in the mechanical assembly and modification of the detector enclosures. Building the junction boxes and assembling the equipment were actually developmental activities, and access to facilities and staff such as those in Los Alamos was essential to the timely completion of the work. When everything had been tested and assembled it was shipped to the Darlington facility.

In parallel with this work, the penetration modules were specified and purchased by the IAEA through the facility. They were installed before the detector enclosures arrived.

Facility personnel filled the D₂O containers when the detector enclosures arrived at the facility. The ICs were assembled and installed. We prepared drafts of assembly and test procedures and developed control and analysis software as work progressed. The detector assemblies were tested as they were completed. Initially things went well, but high-humidity conditions in the assembly area before all the ICs could be sealed created problems. Solutions required much more work

on the part of IAEA staff than was anticipated. A Canadian consultant helped modify the preamplifier capacitors to harden them against humidity and microphonics. The electrical leakage problem with the ICs was solved after a return to Los Alamos to study the problem and to consult with the manufacturer. A problem with small metal flakes from the threads of the fission chambers and high humidity was solved by disassembling the fission chambers and cleaning and drying the ceramic insulators. The diagnosis of the problem took valuable time and required telephone consultations with the supplier. The detector enclosures were finally satisfactorily tested and installed on the walls of the containment. Facility personnel installed the cabling and cable connectors after training by the IAEA technician. Some of the assembly required unique techniques not encountered outside specialized laboratories. Hence the installation took significantly longer than anticipated, and sometimes had to be redone. It should be noted however, that the cooperation extended by the facility was always very good. All cabling was tested jointly by facility and IAEA personnel according to procedures developed and documented in draft form. System testing revealed an electronic noise sensitivity in the monitor subsection. Isolation transformers on the power lines to the GRAND-IIs solved the problem. Noise is still detectable, but it is significantly below the signals seen during refueling. Except for times when the GRAND-IIs have been deliberately shut down, they have been running continuously since November 1988. Interim software was written to test the GRAND-IIs, to temporarily perform limited CFC CDM functions, and off-line data review. Figure 4 shows radiation signatures recorded by the CDM system during reactor startup. The data were plotted using an interim review program implemented using Symphony's macroprogramming language. Changes in reactor operation from 0.1% to 0.6% of full power are clearly identifiable.

Since early 1989, even though the reactor has not been operating most of the time, data have been collected and reviewed to determine the performance of the system. Minor problems have been found and repaired on a "continuous feedback"
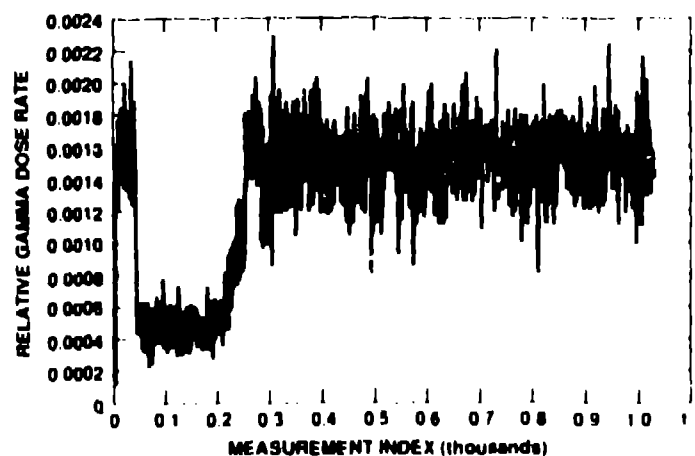

Fig. 4. Data from CDM showing 0.1% to 0.6% reactor power excursion.

basis. That is, the resident liaison reports problems to Los Alamos, and Los Alamos responds informally as time and funding permit. Vienna is kept informed of interactions and progress. This has proven to be effective and efficient because formal overhead is eliminated and the time frame in which problems must be solved is flexible because time is available because the system does not have to be operated for safeguards until after the reactor has operated for 100 full-power days.

A plan for checking the system during commissioning has been developed with the goals of certifying that the system is working as designed and that it is sufficient. In addition, data will be analyzed to find if a more optimal detector configuration can be specified. The commissioning will be done when routine fueling commences. A limited precommissioning test has also been scheduled.

The analysis and use of the large amount of performance monitoring and preventative maintenance data that this system is providing has not yet been addressed. The specification and development of a PERFORMANCE REVIEW program would be a reasonable next step. Such a program patterned after the DATA REVIEW program, which relies on a data base to handle data, could track critical operational parameters and help predict maintenance requirements. The only routine maintenance anticipated is yearly or biyearly replacement of the GRAND-II batteries. Other maintenance should be predicted from the performance monitoring results. We *do not* recommend that maintenance be performed by inspectors. As with other sophisticated safeguards equipment, proper maintenance and care should be the responsibility of professionals specifically trained in the use of the technology.

Existing technology was adapted for this project, and a significant amount was purchased from private industry. The equipment for the second Darlington reactor will be purchased entirely from private industry. The IAEA will supervise its certification and installation. This project will undoubtedly serve as a foundation for more projects of its type.

ACKNOWLEDGMENTS

APPENDIX

A BRIEF ELECTRICAL DESCRIPTION OF THE GRAND-II AS CONFIGURED FOR THE CDM

The GRAND-II electronics package* is 33- by 38- by 12-cm and weighs 9.3 kg (see Fig. A-1). Its batteries allow it to operate for more than 24 hours in the absence of ac power.

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*Available from D. S. Davidson Co., 19 Bernhard Rd., North Haven, Connecticut, Phone: (203) 288-7324.
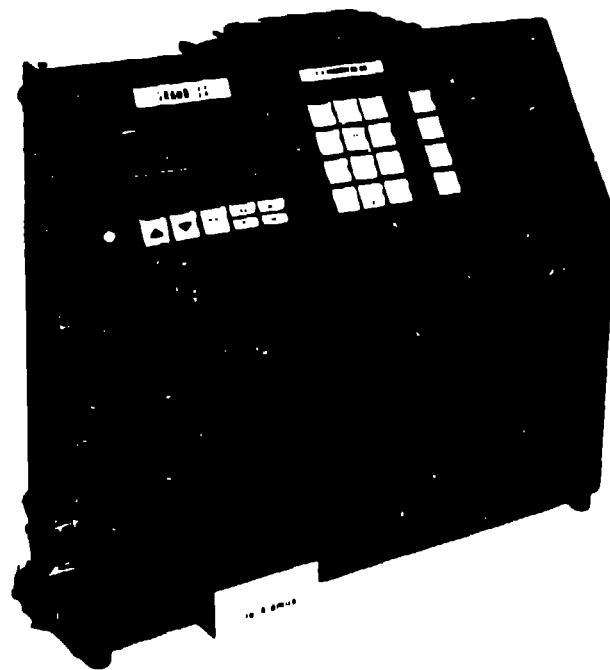

Fig. A-1. The GRAND-II package.

For normal operation, it has a 4-line by 20-character liquid-crystal display and 21 pushbutton keys. It has two serial ports. We use the one implemented for RS-232, RS-422, or an isolated current loop. The port is used to communicate with the CFC. It also has an uncommitted and unbuffered 16-bit bidirectional parallel interface with four handshake lines. In this application, an electronic key is used to permit the serial port access to programmed functions other than CDM functions. It has a main electronics board with processor, battery-backed-up memory, serial and parallel interfaces, and an expansion bus that allows personality boards to be connected and controlled by software.

For the CDM systems, two personality boards were used. One is an IC board with two channels of current-mode input. The dynamic range of these channels is roughly from 3×10^{-14} to 8.6×10^{-5} A. The firmware automatically selects the optimal gain from 12 different choices, each of which differs by a factor of 4 from its neighbors. The dual IC personality board provides a bias that ranges from -50 to -500 V at a single output. It is set manually but is read by the microprocessor with 12-bit resolution. The standard board was modified for CDM use to provide a 12-V disconnect signal for the relay inside the detector enclosure. This relay disconnects the ion chamber from the signal line. This allows leakage currents from the cabling and connectors to be measured, and provides a diagnostic to assure that a signal is coming from the detector and not from a cabling anomaly.

A triple neutron counter personality board is also used. It has three independent pulse-counting channels; each may be controlled by one of two independent processor-selectable time bases. Each channel has a counting capacity of 2^{32} counts. There are many possible input configurations for this board. For the CDM application, the first counting channel is connected to the output of a lower-level discriminator that looks at the output of an on-board analog amplifier connected to the external analog output preamplifier connected to one pair of fission chambers. The second channel is connected to a window discriminator that monitors the same on-board amplifier

output. The first channel is used to count neutrons from the detector; the discriminator is set at the cutoff of the fission chamber's alpha signal. The window of the second channel is set into the alpha signal to provide a continuous signal for tamper sensing. The third channel connects to the digital output of the external digital output preamplifier connected to the detector enclosure, which views the other reactor face. All discriminator levels are controlled through the firmware. This personality board also provides a manually settable single bias output ranging from 50 to 3000 V. Its value is also read by the processor with 12-bit resolution. All voltages including preamplifier output voltages can also be read with 12-bit resolution. The processor can also inject 1-MHz pulses into each of the channels for diagnostic purposes.

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